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Review of impedance source power converter for electrical applications

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ABSTRACT

Power electronic converters have been actively researched and developed over the past decades. There is a growing need for new solutions and topography to increase the reliability and efficiency of alternatives with lower cost, size and weight. Resistor source converter is one of the most important power electronic converters that can be used for AC-DC, AC-AC, DC-DC and DC-DC converters which can be used for various applications such as photovoltaic systems, wind power systems, electricity. Vehicles and fuel cell applications. This article provides a comprehensive overview of Z-source converters and their implementation with new configurations with advanced features, emerging control strategies and applications.

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1. INTRODUCTION

This paper reviews the developments made in the field of Z source converter from the year 2018 to till date addressing several structures with detailed analysis of operations, its switching patterns, modulation techniques, control methods and different applications.

Impedance (Z) source converter was introduced by Peng in 2002 which allows single stage conversion with buck and boost capability and eliminates the need for dead-time protection. The short circuit of leg switches, named as shoot-through, which can be used for boosting the input voltage. Many derivatives of this basic topology are developed by various researchers throughout the world and adopted to all existing types of power converters, i.e., DC–AC, DC–DC, AC–DC, and AC–AC. These topologies are aimed to increase the conversion system reliability and efficiency with decreased cost, volume, and weight. The topologies are used for various applications such as photovoltaic (PV) systems, wind energy conversion, fuel cells, uninterruptible power systems, motor drives, energy storage systems, and power factor correction [1], [2].

Abdelhakim *et al.* has presented classification and review of modulation schemes of the three-phase impedance source inverters. They classified different types of modulation schemes such as three phase leg shoot through based (3P) modulation schemes; and single phase leg ST based (1P) modulation schemes. The existing widely used pulse width modulation (PWM) strategies for Z source inverter (ZSI) includes simple constant boost control (SCPWM), maximum boost control (MPWM) and maximum constant boost control (MCPWM) sinusoidal PWM, sinusoidal PWM with 3rd harmonic injection and space vector modulation

(SVM). The state of the art modulation schemes are simulated using MATLAB/PLECS and experimentally assessed using a 3 kVA three phase ZSI [3], [4].

Li and Cheng have made study on various topologies of improved Z-source inverters and observed its performance through MATLAB simulation and they suggested that diode-assisted extended and embedded ZSI can be used for fuel-cell generation, photovoltaic power generation, wind power generation and other new energy applications [5].

2. Z SOURCE INVERTER TOPOLOGIES

This section deals with design, development and experimental validation of single phase/three phase, modified and special type of ZSI topologies employing either inductors, capacitors and diodes or coupled inductors which have features like high voltage gain, reduced stress on the capacitors and inductors, soft start characteristics, inhibited inrush current, reduced switching losses and having better efficiency and reliability. These inverters will produce three level or higher voltage levels with better waveform quality with low total harmonic distortion. Development of new ZSI topologies by rearranging the passive elements, locating the voltage sources at prominent locations is also discussed. The quantitative and qualitative analysis is done in both the continuous current mode and discontinuous current mode. Operation of these ZSI topologies can be controlled by conventional modulation strategies or any special modulation schemes such as model predictive control or sliding mode control techniques. Simulation of these topologies are carried out in MATLAB/Simulink, PSIM, PLECS, PSCAD/EMTDC platforms and experiment validations are done in DSP/FPGA, Opal RT platform with scaled down laboratory prototype [6]-[42].

Surapaneni and Das had worked out Z source derived coupled inductor based high voltage gain micro inverter. Closed-loop control is implemented with TI DSP 28335 (Delfino) control-card. Agilent Technologies E4360A PV simulator is used on the dc side. An auxiliary multi winding fly back converter controlled by LM5160DNT is designed to supply isolated power to the drivers from photovoltaics (PV) simulator. Experimental results are demonstrated for a 250-W prototype at different operating points, which show that the switch voltage spike is limited and the micro inverter have high voltage gain capability for interfacing the low dc voltage output of PV module to single-phase ac grid [6].

Singh *et al.* presented state space average modeling, design, and operation of a single phase modified ZSI integrated with a split primary isolated battery charger for dc charging of electric vehicle batteries. Simulations and experimental setup are carried out for the operation of a 3.3-kW proposed inverter charger. This topology can be applied to a centralized configuration for charging in semi commercial locations such as a parking lot of a shopping mall. For residential applications, this idea can be extended to string inverters with the charger side of the string inverter configurations connected in series or parallel for current sharing [7].

Bussa *et al.* have developed two single-phase switched LC (SLC)-ZSIs (Type 1 SLC-ZSI and Type 2 SLC-ZSI) to achieve high-voltage gains at low values of D with lower passive component count as compared to SLZSIs. The proposed inverters can be used in various DC–AC and DC–DC power conversions in renewable energy applications due to their high-voltage gain, better immunity to electromagnetic interference (EMI) noise and higher reliability. Scaled down experimentation has been carried out to verify the performance of the proposed inverters [8].

Luong *et al.* introduced a new single-phase five-level Z-source T-type inverter which allows the power switches in a phase-leg conducting simultaneously without any problems. It can produce the buck-boost output voltage with a single-stage power conversion controlled through two shoot-through control strategies. Simulation results using PSIM software are provided along with 400-W prototype to confirm properties of the proposed concepts [9].

Liu *et al.* have summarized of 2 ω power-decoupling techniques for single-phase ZSIs/qZSIs and explained its advantages and disadvantages, possible potential applications. An implementation example of an APF-based three-to-single-phase qZS-MC is also dealt [10].

Deepankar, *et al.* presented a three-winding mutually coupled inductor-based LZSI. For the validation of theoretical analysis, a 540-W prototype is designed and implemented [11].

Zhang had investigated unified control strategy employing space vector pulse width modulation for grid-connected PV system which compensate the reactive power and restrain the current harmonics. Simulation and hardware implementation is carried out based on the digital signal processor (DSP), which can effectively regulate active and reactive power generated by the grid-connected PV system [12].

Ahmad *et al.* had presented three-phase switched-boost modified ZSI topologies such as switched-boost ZSI, DC-qZSI, and CC-qZSI with improved boost capabilities. In these topologies, the voltage gain is increased significantly by adding one auxiliary switch and one diode without using additional passive components. Operating principle, steady-state analysis, voltage gain, voltage stress, current stress, stored

energy analysis, power loss, total harmonic distortion, and efficiency analysis are carried out to highlight the advantages of the proposed inverter topologies as compared to the conventional ZSIs [13].

Ahmad *et al.* have presented two switched ZSI based on capacitor and diode assisted extended type with high voltage conversion ratio having a wide range of duty cycle operation and continuous source current checked with simple boost switching algorithm. Simulation results of capacitor assisted and diode assisted switched capacitor-extended boost are carried for duty cycle at 0.2 and modulation index at 0.8 in PSIM environment and steady state capacitor voltages, AC output voltage, load voltage, load current, voltage across diodes, inductors currents and switch voltages are obtained. The experimental verification is performed using FPGA NEXYS DDR 7 controller [14].

Sajadian and Ahmadi have presented model predictive control of dual mode ZSI with capability to operate in islanded and grid connected mode. The main predictive controller objectives are direct decoupled power control in grid-connected mode and load voltage regulation in islanded mode. The proposed controller offers seamless transition between the two modes of operations without causing significant deviation in voltage and current due to mismatch in phase, frequency, and amplitude of voltages, which was experimentally validated using the PLECS RT Box [15].

Sajadian and Ahmadi have worked out a robust model predictive-based control strategy for grid-tied ZSIs for PV applications with low voltage ride through (LVRT) capability. This system has two operation modes: normal grid condition and grid fault condition modes. In normal grid condition mode, the maximum available power from the PV panels is injected into the grid and the system can provide reactive power compensation as a power conditioning unit for ancillary services from DG systems to main ac grid. In case of grid faults, the system changes the behaviour of reactive power injection into the grid for LVRT operation according to the grid requirements to meet both the power quality issues and reactive power injection under abnormal grid conditions. The system operation is verified experimentally in dSPACE 1006 platform, the results demonstrate fast dynamic response to account the change in solar insolation, small tracking error in steady-state, and simple control scheme [16].

Guo *et al.* have proposed a new modulation strategy named 3D-SVPWM method to reduce the leakage current for Z-source four-leg transformer less PV inverter to achieve the step-up function and constant common mode voltage and suppression of the leakage current. The proposed strategy is digitally implemented and tested on the TMS320F28335 DSP and XC3S400 FPGA controlled hardware platform [17].

Chauhan *et al.* had studied non zero discontinuous inductor current mode in certain Z-source converters in which constant current phenomenon appears, existence condition and case study along with performance parameters analysis [18].

Chen *et al.* proposed an equivalent rule of source placement in different positions of the impedance source network. The rule is feasible to find out all the possible sub networks from its parent-network methodically by just changing the positions of the voltage source. Performance differences of the corresponding sub networks caused by the different positions of voltage source are discussed. Simulations and experiments are implemented with dc load to validate the rule of source placement for the Z impedance source network (ZISN) capacitor assisted quasi Z impedance source network (CAZISN) [19].

Zhu *et al.* have developed a new half-bridge impedance source inverter with high voltage conversion ratio by having small shoot-through duty cycle. The topological configuration, operating principle, power loss analysis, and performance comparison are presented and they suggested that this topology can be applicable for the electrochemical and electroplating applications [20].

Aleem *et al.* presented a new family of impedance source inverters employing a high frequency electrical isolation between the inverter bridge switches and the load along with voltage clamping across the DC-link voltage. In PV systems, the addition of the high frequency transformer provides safety by avoiding the injection of DC circulating current into the grid, without the need of an external bulky line frequency transformer. The gain of this inverter design can be accurately selected by choosing the turn's ratio of the HFT or by adjusting the shoot-through duty cycle (STDC) to the inverter, which a greater freedom especially when utilizing a higher modulation index, with the STDC allowing dynamic gain adjusts to be done speedily during operation of the inverter. This technique provides benefits not only in improving the output voltage quality, but also in reducing voltage stress of the active and passive components by minimizing the voltage spikes across the switching devices. PSIM Simulations are provided for the proposed class of isolated inverters to verify their working along with experimental investigation [21].

Chauhan *et al.* have reported switched inductor-impedance source inverter (L-ZSI) based hybrid converter as a potential candidate for dual output (DC and AC) applications. This converter has two operating modes based on inductor current nature: continuous current mode (CCM) and discontinuous current mode (DCM). Also a modified hybrid L-ZSI (MHLZSI) was reported to demarcate the CCM and DCM, boundary condition based on the average inductor current. Theoretical analysis is presented by taking

into account the effect of inductor current ripple to prove that MHLZSI is capable of achieving higher gain when operated in DCM. Theoretical analysis is validated by experimental analysis [22].

Ho and Chun have presented the topology and maximum boost control based modulation technique for three phase three-level modified Z-source neutral-point-clamped (MZS-NPC) inverter, having twice the value of boost factor and a balanced the dc-link neutral-point voltage. A closed loop control of the ac load voltage in the fuel-cell or photovoltaic applications is realized for the system, in order to supply a desired voltage to the critical load in islanding mode of a microgrid. The boosting ability and operation validity of the proposed topology and modulation technique are demonstrated with PSIM simulation and experimental results with a 32-bit DSP-type TMS320F28335 [23].

Nozadian *et al.* have studied high step-up switched Z-source inverters (HSZSIs) with two main groups namely types I and II used for renewable power systems which has higher boost factor. A new objective function is defined so that all compared parameters can be investigated with each other simultaneously. The power losses and efficiency analyses for all of the proposed structures are done and compared with the conventional structures. It is shown that for Pout of 200 W, the measured efficiencies for basic HSZSI type I, quasi-HSZSI type I, basic HSZSI type II and quasi-HSZSI type II are 91, 85, 96, and 92%, respectively [24].

Bussa *et al.* have proposed enhanced high gain switched inductor capacitor Z Source inverter, which has lesser number of elements to achieve high gain inversion ay low duty region. It gives continuous input current at reduced high frequency ripple. The steady state behavior of this inverter is verified through PSIM based simulation and scaled down 250 W laboratory prototype [25].

Kumar *et al.* have discussed about switched boost inverter for continuous and discontinuous and also for non zero discontinuous current mode (NZ-DCM) of operation. The analytical expression during NZ-DCM is derived and analyzed in terms of peak to peak ripple inductor current. A modified switched boost inverter which consists of an extra active switch antiparallel across the diode is checked through MATLAB simulation and experimental results are presented [26].

Xu proposed five new control methods such as asymmetric a + b method, symmetric a + b method, semi - symmetric a + b method, asymmetric a x b method and symmetric a x b method for single-phase ZSI having optimized closed-loop control scheme with better harmonic elimination performance. Experimental results are obtained from a 1kW un-isolated ZSI prototype have been demonstrated the effectiveness of the control methods which has better performance with reduced harmonics, more flexible voltage gain, and simple algorithm [27].

Yilmaz and Erkmen have analysed an iterative reduction based heuristic algorithm (IRHA) based closed loop control and space vector PWM (SVPWM) control of the ZSI. The third harmonic addition method is used to realize the SVPWM structure in programmable embedded environment. The control parameters are optimally determined by IRHA to overcome the problem of instability. The controllers are implemented in single field-programmable gate array (FPGA) chip using hardware description language without help of any IP core units which increases speed, accuracy, compactness and cost efficiency. Furthermore, power consumption of the controllers is lower than conventional ones which is prominent advantage of employing FPGAs. The effectiveness and accuracy of the control structure are verified by experimental results [28].

Lyu *et al.* proposed a novel permanent magnet synchronous motor (PMSM) driven system based on isolated shoot through Z-source inverter (IST-ZSI) having the features of higher boost factor and modulation but also provide a large regulation range of the output voltage. For the PMSM drive system, a variable damping injection controller is proposed via the passivity-based control and maximum torque per ampere control principle. Then, the load torque observer is designed to improve the stability of the PMSM system with uncertain load torque. The simulation and experimental results show that the variable damping injection control has satisfactory dynamic and static control performance [29].

Chen *et al.* proposes a sliding mode control method with a multi power approaching law (MPAL) for the DC-link control of inverters. This novel approach can solve the slow convergence rate and serious buffeting of the traditional sliding mode control. The proposed approach makes the system state reach the sliding surface rapidly. The inherent buffeting of the sliding-mode control is simultaneously weakened and even eliminated in a few cases. Matlab simulation and Opal RT based experimental analyses prove that the proposed sliding-mode control with an MPAL features significant advantages unlike the traditional sliding-mode control and provides a certain practical value [30].

Asl *et al.* have proposed a new switching pattern for switched ZSIs which can generate general boost factor with different functions. The proposed modulation technique is a general technique and can be applied for all types of switched boost inverters, switched ZSIs and active ZSIs, which does not use additional passive elements in comparison with the conventional ZSI. Moreover, variable boost factor with ability of changing both switching factor and shoot-through duty cycle makes these inverters more valuable

than transformer-based ZSI. The extraction of equations and steady-state analyses for a type of switched ZSIs in different operating modes is presented. In addition, the design considerations and calculation of critical inductance in the new switching pattern are given. The logical diagram of the switching pattern is introduced and comparison between different types of switched ZSIs with the proposed switching pattern from different aspects is done. Finally, the simulation and experimental results are given to show the good agreement between the theoretical and measured results [31].

Kojabadi *et al.* proposed high boost trans-z-source inverter with continuous input current. Because of the high boosting capability of the proposed inverter, the modulation index will be higher with lower shoot-through duty ratio. Higher modulation index will lead to improved total harmonic distortion of the output voltage. The effectiveness and validity of the inverter are provided with experimental and simulation results [32].

Gambhir *et al.* have worked out current-fed switched inverter (CFSI), a derivative of ZSI) having the advantages of lower component count, single stage conversion, high gain, and inherent shoot-through protection. However, due to the limitation of modulation index, CFSI is forced to operate at higher DC-link voltage, which leads to voltage stress across the switches and capacitors. To mitigate this problem, a new PWM technique is proposed, where CFSI can be operated at a lower DC-link voltage by increasing the modulation index, which increases peak-to-peak ripple in the inductor current and leads to condition of early DCM. So a variable duty cycle (VDC) scheme is implemented, which reduces the peak-to-peak ripple in the input inductor current and increases the CCM operating range of CFSI [33].

Kumar *et al.* selected a generalized switched inductor cell for Z-source network for integration. The quantitative and qualitative analysis is done for the proposed converter in both the continuous current mode and discontinuous current mode. The analysis shows that a higher voltage gain can be achieved in the discontinuous current mode as compared to the continuous current mode. To control the proposed converter, two new modulation techniques are proposed i.e. full shoot through and upper shoot through/lower shoot through. Finally, the proposed converter is validated experimentally in both the modes and for different modulation techniques [34].

Ding *et al.* proposed a cockcroft-walton multiplier voltage (CWMV) impedance-source inverter consisting of a modified CWMV circuit and an impedance-source inverter. CWMV qZSI possess continuous input current, small voltage overshoot across the bridge, limited voltage and current stresses on components, higher boost capability. The operating modes of the CWMV qZSI, voltage and current stress of each device are analyzed, the small signal model of the circuit is established, and a PID controller with good control performance is designed. The theoretical analysis was verified by a 1 kW laboratory prototype. The experimental results were consistent with the theoretical analysis [35].

Shuai and Qianfan have analyzed current ripple of ZSI the expression of current ripple is derived and the current ripples of ZSI and voltage-source inverter (VSI) are compared. A variable DC-link voltage and switching frequency method was adopted to reduce conduction and switching losses without increasing the predicted peak current ripple. These theoretical findings were further verified by simulations and experiments [36].

Asl *et al.* proposed double fed and double switch active ZSI having high voltage gain by using improved simple boost modulation technique. Steady state analysis of the inverter in different operating modes such as ST operating mode, adjacent non ST operating mode and non adjacent non ST operating modes are presented. Simulation results using PSCAD/EMTDC software and corresponding experiments are presented to verify its effectiveness [37].

Fang *et al.* investigated a series-type switched-inductor Z-source inverter (SSI-ZSI) topology having better voltage gain, reduced capacitor voltage stress, soft start characteristics, and inhibited inrush current. The circuit structure and operating principle are analyzed in simple boost control scheme in detail through MATLAB/Simulink simulation model and the experimental platforms to verify it's the rationality and superiority [38].

Huynh *et al.* proposed asymmetrical embedded MZS-3LTI (AEMZS-3LTI) and symmetrical embedded MZS-3LTI (SEMZS-3LTI) topologies provide a highly boosted ac output voltage with five voltage levels and ensure a continuous dc source current by adopting the embedded concept. Operating analysis is performed and a comparison of the two proposed topologies with five different topologies combining the impedance network and 3LTI or neutral-point-clamped (NPC) inverter is provided. A novel modulation technique is proposed for effectively controlling the upper and lower shoot-through states with a simple logic circuit and balancing a neutral-point voltage. The validity of the proposed topologies and the modulation technique is demonstrated through PSIM simulation and experimental results [39].

Dong *et al.* have developed switched-coupled-inductor Z-source inverter (SCIZSI), based on the switched-and-coupled inductor technology which has higher voltage-boosting capability, sharing a common ground point between the DC source and the inverter bridge, reduced input diode and capacitor voltage

stress. The operating principles, impedance-network design, voltage and current stress are presented. The theoretical findings were verified by simulation and experimental results [40].

Asghar *et al.* presented LC ZSI with minimized capacitor voltage stress with same boost factor with reduced volume as that of conventional Z source inverter. The advantages of the proposed structure are verified by simulation and implementation [41].

Ding *et al.* proposes extensible Z source inverter architecture (EZSI) which provides high voltage gain at a small shoot through duty ratio, which improves the output waveform quality. EZSI can be constructed with modularity using low voltage components to construct a high power single stage inverter. Experimental verification are carried out for 1 kW prototype to validate the theoretical analysis [42].

3. QUASI Z SOURCE INVERTER TOPOLOGIES

This section deals with design, development and experimental validation of switched/ enhanced/ extended/ cascaded multilevel boost, battery energy stored, Trans, modified, multi input/ multi output, high frequency sic based quasi ZSI topologies for photovoltaic, microgrid applications. Open circuit/short circuit fault diagnosis of quasi ZSI topologies is also dealt [43]-[81].

Nguyen *et al.* have developed two switched capacitor quasi switched boost single phase inverters having the features of continuous input current, high voltage gain with single stage conversion having low voltage stress on active switches, capacitors, and diodes. A 500-W prototype is built to verify its operation in both the standalone mode and the grid-connected mode. Simulations are carried out in PSIM environment and experimental results are done in TMS320F28335 DSP control platform with PI and PLL controller to validate the theoretical analysis [43].

Nguyen *et al.* have introduced high voltage gain quasi-switched boost inverters (HG-qSBIs) controlled through novel PWM control technique, which has characteristics such as: a) continuous input current with low ripple, b) reduced voltage stress on the capacitor, switch and diodes, c) shoot-through immunity, d) achieved high voltage gain with single-stage conversion, and e) improve the output voltage capability with using high modulation index. A 500 W prototype was built in the laboratory to test the proposed HG-qSBI. The PWM control signals of the switches are produced by TMS320F28335 DSP through DE0-Nano FPGA card. Simulation and experimental verifications are shown to prove the accuracy of the theoretical analysis [44].

Zhu *et al.* dealt with a new single-stage high boost quasi-ZSI based on the active switched Z-impedance network which provides higher voltage boost factor, draws continuous input current, shares the same ground between the input source and the bridge inverter with doubled output voltage.It has lower active switching voltage stress, lower passive component voltage ratings and lower shoot-through current stress with lower input current ripple. A laboratory prototype based on the TMS320F28335 DSP was constructed and tested with 60 V dc input and ac 110 Vrms phase output confirmed that the proposed inverter has high boost voltage inversion capability [45].

Dong and Zhang have presented a novel active-switched-capacitor/inductor quasi-Z-source inverter (ASC-qZSI) with an anti-parallel switch which allows both discontinuous conduction mode (DCM) and continuous conduction mode (CCM).Detailed analysis of the voltage regulation capability, inductor current ripples, switching devices stresses, and converter loss are carried on for CCM and DCM, which are verified through simulation and experimental verification [46].

Majeed and Chughtai proposed two new multi-cell schemes for ASC-qZSI and active-switched capacitor/ switched-inductor qZSI (ASC/SL-qZSI) topologies. Detailed theoretical models for the proposed schemes are developed. Appropriate simulations and experimental studies have been carried out which verify the theoretical proposals. The proposed topologies can be useful in practical applications requiring large DC-AC voltage gain for example in renewable systems with low-voltage sources like photo voltaics or fuel-cells [47].

Reza *et al.* have developed quasi switched boost inverter having the features like very low continuous input current, reduced voltage/current stress, shoot through immunity, single stage conversion, and improved voltage quality. The operation, steady state analysis and design guidelines for the proposed converter is explained and demonstrated through 400 W laboratory prototype [48].

Nguyen *et al.* presented a novel PWM control strategy for the DC link quasi switched boost inverter (DqSBI). The modified PWM control strategy based DqSBI improves the voltage gain and reduces the conduction loss and the inductor current ripple. Circuit analysis and comparison study between the DqSBI, the quasi-Z-source inverters, and the two-stage inverter with a boost DC-DC converter are presented. 1 kVA three phase inverter prototypes were set up to compare and evaluate the performance of the DqSBI with the improved PWM method for voltage gains of 0.85 to 1.6. The measured efficiency and total harmonic distortion (THD) values are also presented [49].

Abbasi *et al.* have proposed two topologies namely embedded switched-inductor qZSI (ESL-qZSI) and improved embedded switched-inductor qZSI (iESL-qZSI), find applications in battery-, photovoltaic-, or fuel-cell-powered systems controlled by simple boost PWM control method. Evaluations of these topologies are carried out with PSCAD/EMTDC software which produces extended the voltage gain and reduced ripple content [50].

Gu *et al.* have developed enhanced boost quasi ZSI with an active switched Z-network which has continuous input current, high boost factor and reduced current stress across switches, reduced conduction loss of switches, and improved efficiency. The proposed topology has been simulated on the open-loop configuration using ideal components in the PSIM program and the laboratory prototype was constructed based on a TMS320F28335 DSP with the same operation conditions as for simulation [51].

Zhu *et al.* have proposed a new family of high boost qZSIs with combined active switched inductor boost network which provides continuous input current and higher boost voltage inversion capability, shares common ground between the input source and the inverter bridge, which would be applicable for the renewable energy system with low-voltage distributed dc sources. This topology has higher modulation index with improved output voltage waveform quality, and lower switching voltage stress across the power switches. This inverter uses smaller inductance values compared with the conventional topologies, so the size and weight of the passive components can be reduced. A laboratory prototype based on the TMS320F28335 digital signal processor with 60 V dc input and 110 Vrms ac output was constructed to verify the effectiveness of the proposed inverter [52].

Pan *et al.* have discussed an enhanced-boost bi-directional qZSI with novel active switched inductor (SL) cells (named as Active-SLs qZSI). The proposed active SL cell replaces three diodes in the conventional SL cell of the qZSI with two capacitors and one active switch, thus allowing bi-directional power flow and achieving higher boost factor. The Z-source network (ZSN) diode is also replaced by an active switch. This active-SLs QZSI has less current stress of ZSN, higher efficiency and higher boost factor. A modified Space Vector Modulation (MSVM) is introduced to reduce the switching frequency of active switches of ZSN. Both simulation and experimental results validate theoretical analysis of the proposed active-SLs QZSI [53].

Ho and Chun had developed single-phase MqZS hybrid three-level inverter which provides higher boost ability and reduces the number of inductors in the source impedance, when compared with single phase three-level neural-point clamped qZSI and single-phase quasi-Z-source cascaded multilevel inverter. Additionally, the developed inverter can be extended to obtain the nine-level output voltage by cascading two three-level pulse width modulation switching cells with a separate MqZS and a dc source. A modified modulation technique based on an alternative phase opposition disposition scheme is suggested to effectively control the shoot-through state for boosting the dc-link voltage and balancing the two series capacitor voltages of the MqZS. The performances of both MqZS-CHI and modulation techniques are verified through PSIM simulation and experimental results controlled by 32-bit DSP type TMS320F28335 [54].

Ge *et al.* have evaluated state of charge (SOC) balancing control method for a battery energy stored quasi Z source cascaded multilevel inverter based photovoltaic power system(qZS CMI PV). This technique is used to manage all the batteries with identical SOCs during properly compensating fluctuations of PV power. The control method is on the basis of battery SOCs, SOC limits of each module, and the total power injected into the power grid. The control strategy of the battery energy stored qZS-CMI PV power system includes the distributed MPPT control, the grid-injected power control of the system, and the battery energy management of each module. The elaborate battery SOC control ensured all the batteries operating in safe area with the same SOC, even with intermittent PV power. The control also maintained grid-tie power integration with low harmonics for the qZS-CMI PV system. Simulation and experimental results verify the proposed control method that ensures identical SOCs for the battery energy stored qZS CMI PV system [55].

Liang *et al.* have worked out an analytic model to investigate the 2ω voltage and current ripple of a battery energy-stored single phase quasi-Z-source (BES-qZS)-based photovoltaic (PV) power generation system [56].

Guisso *et al.* have proposed single DC source quasi-Z-source cascaded multilevel inverter (SS qZS-CMI) which performs at maximum power point tracking of the PV array with a single inverter module and each of the inverter modules shares an equal amount of the power of the whole system. This inverter has the capacity to equally regulate the peak voltage on each inverter module by means of the dual control loop of the main inverter module and the shoot-trough state of the auxiliary inverter modules, ensuring the symmetry of the cascaded multilevel inverter verified through simulation and experimentation using the TMS320F28335 digital signal processor [57].

Uno and Shinohora proposed a novel module integrated converter based on cascaded qZSIs with differential power processing (DPP) capability. A traditional qZSI and voltage multiplier (VM)-based DPP converter are integrated into a single unit with sharing active switches and magnetic components, achieving system- and circuit-level simplifications. A 150-W prototype for a standard PV panel consisting of three

substrings was built, and experimental tests are performed emulating partial shading conditions. The results demonstrated that the proposed integrated qZSI could perform MPPT with satisfactory preventing partial shading issues while generating ac voltage at the inverter output [58].

Singh and Jain presented neutral point clamped quasi-Z-source (NPC-qZS) inverter for renewable energy applications because it yields a continuous input current and voltage boost. A closed loop control of grid-tied three-phase (3-ϕ) NPC-qZS inverter, fed with renewable energy sources, is proposed which has the dynamic model for accurately designed control strategy. The proposed strategy includes the control of grid-tied current and the peak dc-link voltage (PDV). The control of grid-tied current is achieved through a damped-second order- generalised integrator. The PDV is estimated indirectly from the voltages of qZS network capacitors and is regulated by an integral-double-lead controller. Two modified modulation techniques based on phase-opposite disposition and in-phase disposition are proposed to yield shoot through by injecting 3rd harmonics for maximum constant boost control. A comparison is drawn between the performance of the proposed controller and sliding-mode controller on the dc side. The controller design and system performance are validated through real-time simulation and experimentation on a practical setup in the laboratory [59].

Liang *et al.* proposed single-phase energy stored quasi-Z-source cascaded H-bridge (ES-qZS-CHB) inverter PV power system with active and reactive power control which operates both at day and night. The ES-qZS-CHB inverter PV power system usually employs the unity power factor control method to ensure the output current tracking the desired reference in phase with the grid voltage, combining with distributed maximum power point tracking (MPPT) to determine the values of shoot-through duty ratios. These cannot operate at night because there is no PV power input. Meanwhile, as multiple combinations of Dn and modulation ratio Mn could achieve the same voltage gain at night operation. The working approach is: First, a comprehensive control scheme, which addresses the day and night operation, active and reactive power control simultaneously, is proposed; then, an optimization of night operational ES-qZS-CHB inverter to achieve optimal combination of Dn and Mn. Simulation and experimental results validate the day and night operational ES-qZS-CHB inverter and the proposed optimal control technique [60].

Hu *et al.* have modelled and analyzed an energy stored quasi Z source converter with the battery. The impact of the network internal resonance on the battery current control loop is explored. An active damping technique is validated experimentally to ensure the extended bandwidth and better dynamic performances under different state of charge occasions, which was verified by the simulations and experiments [61].

Wolski *et al.* had discussed switching performance and power losses of Silicon Carbide (SiC) MOSFETs in a high-frequency qZSI operating at unity power factor. Also a novel modulation method with minimum number of hard switching transitions is developed and illustrated with experimental results of a 100-kHz/6-kW qZSI built with SiC elements having high voltage boost (B= 1.9) and efficiency reaches 97% at nominal conditions [62].

Wolski *et al.* have compared three inverter topologies such as qZSI, voltage source inverter with a boost converter and a voltage source inverter with an interleaved boost converter. Experimental results obtained from laboratory tests of equivalent 6-kW 100-kHz inverters based on SiC MOSFETs and Schottky diodes are provided. Results of the experiments show that the quasi ZSI topology has input inductor current quality, output voltage quality and also power losses (at high values of input voltage) [63].

Duong *et al.* proposed an improved PWM scheme for an AqZSI with improved PWM strategy can operate in a wide range of input voltage with higher efficiency. AqZSI can operate with a higher modulation index, a lower inductor current stress, and a reduced shoot-through current. SiC-based three-phase inverter prototypes of rating 1.2 kVA are built to verify the agreement between theory and measurement [64].

Liang *et al.* explored the double line frequency (DLF) transfer routes in the impedance source network. A comprehensive stress derivation of the passive components and switching devices are obtained for the suppression method enhancement and optimization. For the DLF passive suppression method, the explanation for the passive component volume issue is provided from the stress aspect. The component value solution space and corresponding design guidance are presented. For the DLF active suppression method (ASM), a buck-type dc-side ASM suppression method is employed and its optimization is demonstrated with the assistant circuit stress analysis. The total capacitor and inductor values get reduced by 77% and 25%, respectively. The corresponding pulse width modulation method implementation and the common-mode leakage current demonstration are also presented. The effectiveness of the theoretical analysis and optimization methods is verified by simulations and experiments [65].

Komurcugil *et al.* have developed a model based current control approach with a compensating of dc-side inductor current ripple, active damping, and virtual time constant for single-phase grid-tied quasi-Z-source inverters with an LCL filter. Experimental results are presented to show the validity and performance of the proposed control approach [66].

Jain *et al.* had proposed a predictive power control algorithm that decouples active and reactive power for grid integration of PV systems using a qZSI. The proposed controller uses model predictive control to ensure maximum available power harvested from the PV array and also to control the active and reactive power injection into the grid to compensate reactive power required by local loads to enable stable operation of the grid at the point of common coupling. The proposed controller has the features like simple structure, fast dynamic response under changing sky condition, and negligible tracking error in steady state. Its performance is experimentally verified in dSPACE-DS1007 platform and the grid-side power quality is evaluated which meets the IEEE-519 standard [67].

Bayhan and Komurcugil proposed double-line frequency (2ω) ripple suppression and SMC with time-invariant (fixed) switching frequency methods for single-phase grid-connected three-level neutral-point clamped qZSI. The 2ω ripple suppression method is based on the 1800 phase difference existing between the 2 ω ripple components of the capacitor and inductor voltages in the dc-side. Hence, when these components are added in the closed-loop, a phase cancellation occurs so that the inductor current reference can be generated without 2 ω ripple component. In this case, the actual inductor current, which is forced to track its reference, has no 2 ω ripple component. In addition, the grid current control is achieved via sliding mode control (SMC). Unlike the existing SMC methods, the proposed SMC achieves fixed switching frequency which is made possible by eliminating the discontinuities in the sliding surface function using a boundary layer. The proposed ripple suppression method together with the SMC method offers many advantages such as fast dynamic response, zero grid current error, simple implementation, robustness to parameter variations and fixed switching frequency. The effectiveness of the proposed control method is verified experimentally under steady-state and transient conditions [68].

Liang *et al.* have discussed about the working of single-phase, qZSI, PV power system with integrated battery energy storage (BES), abbreviated as BES-qZSI-PV power system in day and night conditions by modifying its power circuit and developed the qZS network parameters' design to limit the double-line frequency harmonic at the dc side. A control strategy to ensure the high-performance operation of the system at all times, is also proposed. Based on an experimental platform of single-phase BES-qZSI-PV power system, three groups of experimental tests with different qZS network parameters and battery voltages are carried out to verify the model and parameters design method by means of comparing the experimental, circuit-based simulated, and model-based calculated results. The proposed BES-qZSI-PV system performance is experimentally evaluated in steady-state operation and day-to-night transit operation, as well as by the power efficiency curves in day- and night-modes [69].

Xiao *et al.* proposed a novel variable dc-link voltage control method which can indirectly adjust dc-link voltage with an extra PI-regulator. Basic principle of the method is introduced and two design rules of the PI-regulator are illustrated. The proposed method gets rid of the dependence on an extra voltage sensor to measure the input voltage and can reserve fewer margins for the dc-link voltage, which contributes to less cost and higher efficiency of the drive system. Experiments are performed to validate the feasibility and effectiveness of the proposed method [70].

Vadi *et al.* have evaluated different control methods for the elimination of ripples that occur at 2ω frequency, both on the perspective of DC control side and AC control side thorough a comparative analysis with existing results. Model of single phase QZS inverter and closed-loop control methods of the inverter are examined and compared with PWM methods. These control methods are used to eliminate the ripples at 2ω frequency in the inverters, and the advantages and disadvantages of these methods are presented [71].

Lashab *et al.* have developed dual input quasi ZSI to harvest more PV power through full utilization of the employed qZ-network in the classical ZSI. This modification offers higher conversion efficiency since the current in the second qZ-network's inductor is smaller. The voltage of the added PV array is independent of the voltage of the primary array in a wide range, which promotes tracking their maximum power points (MPPs) separately, achieving a higher efficiency even under partial shading. A novel MPPT technique for two PV sources involving four parameters is worked out. The theoretical analysis is validated through real-time hardware-in-the-loop tests using PLECS – RT tool box, and it demonstrates that at least 11% more power can be harvested compared to the conventional qZ-network-based impedance source converters [72].

Bagheri *et al.* developed a multi-input multi-output (MIMO), SMC methodology with constant switching frequency for single-phase qZSI. The mathematical model of the entire system is derived in state-space form. The proposed SMC is capable of controlling both dc and ac sides of the system concurrently. The proposed control does not require proportional-integral (PI) controller in the dc-side. Furthermore, it offers several advantages such as simple implementation, reduced gain requirement, robustness against system parameters, and zero steady-state error in the load voltage. The fixed switching frequency is attained by altering the sliding manifold behavior inside a boundary layer. The power balance equation is used to generate the dc side inductor current reference. The feasibility of the proposed control method is investigated experimentally when qZSI feeds linear and nonlinear loads [73].

Shiluveru *et al*. presented two hybrid multi output buck-boost quasi z-source converters (q-ZSCs) capable of giving two dc and one ac outputs simultaneously from a single dc input. The rationale behind these hybrid multi output q-ZSCs is to have more flexibility on voltage gains as per the load requirements. All the three outputs of the proposed converters can be independently controlled making them suitable for various applications. These proposed converters are derived from the quasi z-source concept and hence inherit all the properties of q-ZSI which realize buck/boost, single-stage inversion, and power conditioning with improved reliability along with inherent shoot-through protection capability. Detailed steady state operation, loss/efficiency analysis of the proposed converter and discussion on the hybrid pulse width modulation is presented. A detailed comparative analysis among the proposed and other closely related existing multi output converters is carried out. A 310 W prototype is developed to verify the performance of the proposed multi output buck-boost q-ZSC. The proposed converters can be utilized for various modern multi output DC-DC and DC-AC power conversion applications such as renewables and uninterrupted power supplies [74].

Sonkar *et al.* proposed two 3-φ qZSIs with multiple ac outputs. The proposed topologies are developed from qZSI to obtain parallel mode and series mode 3-φ multi-output inverters. In parallel mode, the topology yields n-number of parallel ac outputs with different voltages and currents for different load conditions. For series mode, topology yields n-number of series ac outputs with same voltages and same load currents. The proposed inverters employ sinusoidal pulse width modulation with constant frequency shoot-through scheme for generating switching signals. The proposed inverters can be used for simultaneous multiple dc/ac power conversion for three-phase microgrid applications and three-phase residential loads. The proposed topologies with closed-loop control have been implemented for two inverter units, which is capable of supplying two ac outputs simultaneously. The mathematical modelling of the proposed topologies is carried out for performance analysis. The experimental results of 240 W lab prototypes have been presented to validate the proposed three-phase multi-output qZSIs [75].

Fang *et al.* have presented single-stage boost Tran’s quasi- Z-source inverter topology by describing its basic structure, working principle and its voltage gain is deduced. MATLAB/Simulink simulation is performed to verify the dynamic boost characteristics and experimental results are conducted to verify the feasibility and stability of the circuit [76].

Liang *et al.* has presented small-signal modeling for the bidirectional qZS by the circuit-averaging technique. It is revealed that the oscillation in the modulation ratio could be triggered by the ac current controller, due to the magnitude margin issue caused by the impedance network, and then instability in the impedance network can be observed, including the system input current, which is validated experimentally [77].

Mahmoudi *et al.* have presented a torque ripple minimization method for a permanent magnet synchronous motor (PMSM) drive system that utilizes a modified qZSI. The proposed modified qZS network is designed by adding an extra switching device to the conventional qZS topology and provides a wider range of capabilities for inverter input voltage control e.g. both step-up and step-down operation. It also allows for modification of the traditional switching sequence selection scheme when using the SVM for switching. The provided flexibilities are leveraged to develop a control system that minimizes the torque ripples during PMSM operation while satisfying conventional control objectives such as shaft speed control. The control system is comprised of an input voltage optimization subsystem with the goal of torque ripple minimization which provides the reference for a cascaded modulated model predictive control (MMPC) subsystem for the modified qZS network control, and a motor side predictive control subsystem. The control system employs a new switching sequence selection scheme for SVM modulation to further reduce PMSM torque ripples. Experimental results are provided to validate the theoretical outcomes [78].

Zhu *et al.* proposed a new high boost qZSI with combined two quasi-Z-source networks, which has a common ground between the input source and the inverter bridge, having higher boost capability, requires smaller inductance and capacitance values at the impedance network, achieves lower voltage stress across the active switching devices, and has higher modulation index for the inverter bridge to improve the output waveform quality. The topological configuration, operating principles, power loss analysis, and performance comparison with other high boost (q) ZSIs are presented. Simulations and experimental results are made to validate the aforementioned characteristics [79].

Yaghoubi *et al.* proposed open-circuit fault diagnosis in a three-phase qZSI. This method is more cost-effective since no ultra-fast processor or high-speed measurement is required and it is independent of the load condition. The proposed algorithm includes two consecutive stages: open circuit detection and fault location identification. When both stages of the open circuit fault diagnosis algorithm are done, a redundant leg is activated and utilized instead of the failed leg. The accuracy of the method is confirmed by the experimental results from a low-voltage q-ZSI prototype [80].

Noroozi *et al.* proposed cost-effective solution for short-circuit fault diagnosis in a three-phase qZSI. The fault is announced to the processor utilizing a peripheral circuit which covers the fault detection in all switches of the inverter. After the fault detection, a non-maskable interrupt is activated, cutting the central processing unit (CPU) routine, and a fault-diagnosis algorithm is initiated. The exact location of the failed switch is identified through the proposed algorithm. The entire process is accomplished in advance of the critical over-current condition, which typically arises after a short-circuit fault. AqZSI prototype is implemented to verify the satisfactory performance of the proposed method [81].

4. OPERATION AND CONTROL OF Z SOURCE BASED MATRIX CONVERTER FOR ELECTRICAL APPLICATIONS

This section deals with operation, control and experimental investigation of Z source-based matrix converter for electrical drive applications [82]-[87]. Srividhya and Venkatesan have described the flow control of dye in the paper mill with qZS indirect matrix converter (QZSIMC) fed induction motor drive. The implementation of space vector modulation operated QZSIMC adjustable speed drive with 4-kW prototype controlled through fuzzy logic, and tested at different voltage sag conditions by simulation in MATLAB, Simulink platform. Experimental setup is executed with the aid of a TMS320F2812 (Texas Instrument) processor, and the results validates that the maintenance of speed of an induction motor at the set condition, thus controlling the perfect flow of dye in paper manufacturing technology [82]

Guo *et al*, proposes an induction motor drive system based on the LC filter integrated quasi-Z source indirect matrix converter (QZS-IMC). The proposed drive system shows the following features: a) variable voltage control of inductor motor is achieved by the rectifier stage and variable frequency control is achieved by the inverter stage, b) automatic low voltage ride through ability enhances capability of the proposed drive against grid voltage sag, c) wide voltage gain range ensures the drive system with high performance in wide speed range, d) there is no additional input filter. The voltage control implementation in the rectifier stage is proposed to benefit low voltage stress and low converter loss. The control method combines motor vector control, minimum shoot-through duty cycle and maximum modulation indexes. As a result, the input power supply voltage and dc-link voltage are maximally utilised and the power loss is reduced. Simulation and experimental results verify the proposed QZS-IMC motor drive system [83].

Liu *et al.* have worked out qZS three-to-single-phase matrix converter with low-frequency ripple power compensation through model predictive control to eliminate the low-order harmonic components from the three-phase input currents and voltages [84]. Guo *et al.* had proved abilities of qZS indirect matrix converter (QZS-IMC) such as voltage boost, current filtering, variable voltage, and variable frequency by finding the optimal operation curve of D based on the constrained optimization theory. Simulation and experimental results are validated for the theoretical analysis, the optimal control, and the power loss reduction of the QZS-IMC [85].

Bozorgi and Farasat had investigated cascaded Z-source ultra sparse matrix converter (ZSUSMC) in buck and boost modes of operation controlled by space vector modulation. They also carried out hardware-in-the-loop studies of a ZSUSMC based permanent magnet synchronous motor drive to evaluate its performance. Comparative studies between the proposed modulation schemes are carried out on an HIL setup, which is comprised of an OP4510 real-time simulator from Opal-RT Technologies Inc. and a TI TMS320F28335 DSP [86].

Bozorgi and M. Farasat had evaluated the performance of Z-source ultrasparse matrix converter (ZSUSMC) by implementing through the improved design and controlled through space vector modulation. Here, HIL tests are carried out to evaluate the performance of the ZSUSMC under the developed modulation schemes and verify the effectiveness of the proposed design procedure in satisfying the current quality requirements of the converter. Input voltage source, input filter, and the ZSUSMC feeding an RL load are modeled on an OP4510 real-time simulator from Opal-RT Technologies, Inc., and the control strategy is executed on a single TI TMS320F28335 DSP. It is verified that by employing the proposed modulation techniques, the converter dynamics can be controlled over a wide range of voltage transfer ratios with high-quality input/output currents and unity input power factor [87].

5. DISCUSSION ON VARIOUS MODULATION SCHEMES IMPLEMENTED FOR THE CONTROL OF Z SOURCE CONVERTERS

This section deals with discussion on various modulation schemes implemented for the control of Z source converters such as modified PWM techniques, space vector modulation strategies such as ZSVM1, ZSVM2, ZSVM6, ZSVMD1, ZSVMD6 ZSVM3, model predictive and sliding mode control techniques to improve voltage gain, achieve better controllability and reduction of common mode voltage and leakage

current in photovoltaic systems. Simulations are carried out in MATLAB/Simulink, PLECS, PSCAD/EMTDC and experimental results are carried out to verify the effectiveness of the proposed control strategy [88]-[122]. Zhang *et al.* had analysed improved PWM strategy which yields higher operating efficiency for ZSI analyzing voltage gain, inductor current inrush, capacitor voltage stress. Simulations and 2.5 kW laboratory prototype of ZSI is tested with control board based on DSP28335 [88].

Nguyen and Choi had implemented a new pulse width modulation control scheme for the quasi-switched boost inverter (qSBI) operated at large modulation index, to produce regulated output AC voltage at reduced stress across the capacitor, diodes, and switches, reduced inductor current and capacitor voltage ripples, tested through a 400 W prototype based on a TMS320F28335 DSP [89].

Mohammadi *et al.* have developed novel dual switching frequency modulation (i.e) combination of high-frequency PWM (for input side) and low-frequency SPWM strategies (output side) with different carrier frequencies for Z source and qZSI. This method is especially beneficial for applications in which no output filter is required or at least small filters can be used (e.g., motor drives); however, it may not improve the performance of the inverter for the application in which a bulky output filter is required. A 300-W experimental prototype is designed and tested in the laboratory with gate source pulses were produced by an ARM-based STM32F407VGT6 from STMicroelectronics [90].

Zhou *et al.* proposed a time-variant shoot-through pulse width modulation strategy for the traditional modulation techniques used in qZSI to reduce the .bus voltage amplitude at the nonpeak areas, so that switching loss can be greatly saved to improve system efficiency with increased output voltage gain. Theoretical analysis and experimental results are presented to verify the real performance with the help of 1 kVA prototype of qZSI [91].

Liang *et al.* have developed dc-link voltage balancing control strategy for quasi-Z-source cascaded H-bridge (qZS-CHB) inverter PV power system by using multidimensional pulse-width modulation (MD-PWM) technique. The qZS-CHB PV system usually employs proportional-integral (PI) regulators based closed-loop control methods to balance dc-link voltages, combining with distributed maximum power point tracking and grid-tie power control. When compared with the state-of-the-art of voltage balancing control methods, the proposed control strategy has advantages: a) The computation is low because there is no PI controller, while the stability of the whole system is improved, and b) there is a reliable balancing capability with fast regulation of dc-link voltages, owing to no extra controller parameters and handling the voltage balance in each control cycle. Simulation and experimental results of qZS-CHB inverter based grid-tie PV power system verify the proposed dc-link voltage balancing control technique [92]

Nguyen *et al.* proposed a novel family of PWM strategies for single-phase quasi-switched boost inverter (qSBI). By combining shoot-through mode in the inverter's switches and the turning-on state of an additional switch, qSBI produce a high voltage gain without adding any passive components. A 500-W laboratory prototype is constructed and the effectiveness of the introduced PWM strategy is validated. It is found that qSBI with the proposed PWM strategies is suitable for applications where the required voltage gain lies between 2 and 3 [93].

Nozadian *et al.* presented modified switched boost inverter tested with various modulation control methods such as simple boost, maximum boost, maximum boost with third harmonic injection, maximum constant boost, maximum constant boost with third harmonic injection. The voltage and current equations of all elements in the proposed structure based on the three switching methods are derived and power loss analysis of SM-SBI is also presented. Simulation results by using PSCAD/EMTDC software are presented as well as the experimental results [94].

Chen *et al.* have presented a high frequency isolated qZSI suitable for photovoltaic generation system because of its ability for high lift to voltage ratio, transient bridge direct access and electrical isolation. For the optimization of electromagnetic compatibility of high frequency isolation qZSI, using PWM chaotic modulation technology, using Chen multi-scroll chaotic system and traditional PWM are combined, to inhibit EMI from the noise source, effectively reduce the high frequency isolation qZS switch frequency and its harmonics noise power, and optimize the total harmonic distortion (THD) of the output current by analyzing the chaotic modulation coefficient. The correctness of the theory is verified by Saber simulation. They also provided guidelines for the electromagnetic compatibility (EMC) design of the high frequency isolated quasi Z-source inverter and provide the theoretical basis for the EMI optimization design of the power electronic system [95].

Do *et al.* proposed a new optimal PWM scheme for a three-level quasi-switched boost T-type inverter (TL qSBT2I) under normal and failure modes. The proposed method reveals its semiconductor fault tolerance capability in open-circuit fault condition situations.The PWM control algorithm for the fault-tolerant qSBT2I is implemented by selecting appropriate values for the modulation index, shoot-through (ST) duty cycle and duty cycles of two additional switches. The steady-state analysis and operating principles of

the fault-tolerant qSBT2I are presented. A 1 kW laboratory prototype was built to verify the operating principles of the qSBT2I with the proposed modulation scheme before and after fault conditions [96].

Zhang *et al.* have developed a new space vector modulation, named ZSVM3, for three-phase quasi-Z-source rectifier (qZSR) in which all switches in the three-phase bridge can be turned on and turned off with zero-current or zero-voltage without any auxiliary circuit. The operation principle of qZSR is analyzed through PLECS simulation, simulated switching and conduction losses distribution of qZSR working with different modulations under full load are obtained and the results are verified by a 2 kW prototype for on board charger in electric vehicle applications [97].

He *et al.* had tested three space vector modulation strategies such as ZSVM1, ZSVM2, and ZSVM6 and proposed ZSVMD1 and ZSVMD6 to reduce inductor current ripple of Z source inverter by using the principle of volt–second balance through simulation and experimentation using TMS320F28335 digital signal processor, and an intelligent power module, PM50CLA120, as the main power switching device [98].

Abdelhakim *et al.* have proposed two modified space vector modulation strategies, aimed to reduce the qZSI's number of switch commutations at high current level for shorter periods during the fundamental cycle, to achieve a single switch commutation at a time. These modulation strategies are analyzed through simulation using MATLAB/PLECS models, where a 1 kVA three phase qZSI is utilized for the experimental validation [99].

Qin *et al.* have worked out quasi- Z-source three-level T-type inverter with a SVM scheme to reduce the magnitude and slew rate of common-mode voltage (CMV) and high dc-link voltage utilization can be maintained. The proposed scheme has been verified in both simulations and experiments [100].

Sabeur *et al.* proposed new control method for the Z-source/qZSI, named as one dimension space-vector pulse width modulation (SVPWM) (OD-SVPWM) based on the single phase modulator technique to obtain maximum voltage gain by the carefully selected shoot-through states. Simulation using MATLAB/Simulink and experiment are carried out to demonstrate the validity and feasibility of the control algorithm under different modulation index values [101].

Shults *et al.* presented new space vector pulse-width modulation strategies for a single-phase three-level buck-boost neutral point clamped inverter coupled with impedance source networks. These strategies can be implemented for systems with any impedance source networks with neutral point. Simulation and experimental results confirms that the theoretical prediction to validate the method has reduced switching number, without output voltage quality distortion [102].

Iijima *et al.* proposed a new version of space vector switching strategy for the ZSI, which has unequal short-through intervals to reduce the current ripple in the inductor of its impedance source. The proposed method can reduce the inductor current ripple by 27.8% compared with the conventional method that has equal short-through intervals without increasing the number of inverter switching. The proposed operation and ripple reduction were confirmed in experiments with a 3-kW-class laboratory prototype [103].

He *et al.* have proposed an improved space vector modulation, namely M-ZSVM1, to suppress the dc-link voltage sag under a light load which happens due to diode current interruption. Therefore, an asymmetric shoot-through state distribution method is presented to achieve the minimum current ripple, which can increase the diode current. The qZSI can work properly without the dc-link voltage sag under wide load range, improving the safety and reliability of the qZSI. Simulations and experimentation are carried out to validate the working of the proposed scheme with improved efficiency [104].

Singh and Sonar proposed the use of advanced bus clamping switching sequences to reduce the impedance network inductor current ripple of the three phase ZSI. Here maximum constant boost control method is used for the voltage boosting. The switching sequences are designed in such a way that, it offers around 34 percent reduction in the maximum instantaneous inductor current ripple. The factor of percentage reduction in the inductor current ripple using proposed technique is constant over the entire range of shoot through duty ratio (0 to 0.48). Theoretical findings have been verified using simulation and experimental results. Texas instrument's digital signal processor, TMS320F28379D has been used for the generation of gating pulses [105].

Duong *et al.* introduced a novel space vector pulse-width modulation for the modified qSBI to reduce the magnitude of common-mode voltage and push the modulation index up to 1. By properly choosing the shoot-through interval time, shoot-through states are considered to be inserted for boosting voltage and also reducing the THD value of the output voltage. The mathematical analysis and operating principles of the converter are discussed and verified through PSIM simulations. Finally, an experimental prototype is validated based on a TMS320F28335 DSP microcontroller and a DE0-Nano FPGA digital control platform [106].

Liu *et al.* proposes a generalized SVM strategy for the three-phase qZSI, which can reduce the inductor current ripples by limiting the peaks in different sectors of the vector space. The proposed SVM strategy can minimize the current ripple, while maintaining the same total shoot-through time and it can

ensure the inductor current ripples are always smaller than the peak of the inductor discharging current ripple in a switching cycle. The proposed SVM strategy is derived in details and compared with the conventional ZSVM6 strategy. Simulations and experimental tests are presented to verify the effectiveness of the proposed modulation strategy for inductor ripple current reduction [107].

Lashab *et al.* have described finite-control-set based model predictive control based techniques for ZSI to ensure maximum power point tracking for PV systems. The dynamic simulation is done by using a developed mathematical model of the PV array and the data sheet of the total energy TE 600 PV module is used to emulate the behavior of a real PV string. For experimental setup, Agilent E4360A PV simulator with two channels, each channel provides up to 600-W power (120-V, 5.1-A), a 400-W prototype dc–dc boost converter, which has been made to extract the local maximum power of a real PV panel, and a resistive load is employed. The static and dynamic performance of the trackers is assessed according to the EN 50530 standard, using detailed simulation models, and validated by experimental tests [108].

Karamanakos *et al.* presented a variable switching point predictive current control for the qZSI of rating 3 kW(qZSI), which aims to remove the output current error on the ac side, as well as the inductor current and capacitor voltage errors of the quasi Z source network on the dc side of the converter. The three-phase insulated gate bipolar transistor (IGBT) bridge Powerex IPM PM300CLA060 module and the RURG3060 diode are used as power switches on the ac and dc side of the converter, respectively. This control scheme can directly apply the switching signals not only at the discrete time instants, but at any time instant within the sampling interval. Experimental results based on field programmable gate array, Cyclone III-EP3C40Q240C8 are provided to verify the effectiveness of the approach with RL load which leads to lower inductor current ripples and less output current total harmonic distortion when compared with the conventional direct MPC [109].

Liu *et al.* have discussed discrete time average model based predictive control for the qZSI. The proposed control method predicts future behaviors of ST duty cycle and modulation signals, based on the established discrete-time average model of the quasi-Z-source inductor current, the quasi-Z-source capacitor voltage, and load currents. The prediction actions are applied to the qZSI modulator in the next sampling instant, without the need of other controller parameters' design [110].

Mahmoudi *et al.* presented a modulated model predictive control (MMPC) based control system for the ZSI based PMSM drive system. This approach uses two separate MMPC loops: a) For the Z-source network, a cascaded MMPC control scheme to provide fast and stable response, b) For the PMSM control, an MMPC controller uses the discretized equations of the PMSM to predict the future value of PMSM current vectors, selects specific current vectors that minimize a certain cost function the most, and performs modulation between them during a sampling time. Experimental results are provided to validate the theoretical outcomes [111].

Ramírez *et al.*, presented a predictive control strategy with integral action that compensates for the differences between the estimated model and the inverter with the objective of achieving zero steady-state error without requiring external loops or state observers. This strategy is tested on a single-phase Z-source inverter to evaluate the error in both the ac and dc controlled variables with respect to their references to their co-signs. The experimental results confirm that the proposed strategy achieves zero error in steady state while maintaining the fast dynamic response of the classic predictive control [112].

Noroozi and Zolghadri had employed a novel modulation technique based on odd pulse width modulation and made a minor change in the Z network of the three-phase q-ZSI, the leakage current is blocked. The leakage current is aroused due to CMV fluctuations through the stray capacitance of the PV panels happen in the transformer less grid-connected PV systems. Experimental results for CMV analysis in a 1 kW prototype are presented to verify the theoretical analysis. TMS320F2808 is used as the main controller, providing the switching and the protection commands. The PV input voltage is modeled with a dc supply voltage. The module FSBS15CH60 from FAIRCHILD is used as the power converter, at the bottom of the main board. The voltage variations of CMV are compensated with the inductor connecting to the negative terminal [113].

Qin *et al.* have proposed a novel modulation for quasi-Z-source three-level T type inverter to realize voltage boosting, to reduce the CMV and also to control the neutral-point voltage balance simultaneously. The proposed scheme adopts large vector, medium vector, small vector with low CMV magnitude, zero vector, and shoot-through vector to generate the output voltage. Shoot-through states are inserted within zero vector to boost the dc input voltage without affecting the ac output voltage. The CMV magnitude can be restricted within one-sixth of dc link voltage, and neutral-point voltage imbalance can be effectively mitigated and the effectiveness of the scheme is verified by MATLAB/Simulink simulations and experiments are controlled by dSPACE DS1005 and FPGA DS5203 [114].

Bozorgi *et al.* had discussed about modulation techniques for CMV reduction in Z source ultra sparse matrix converters (ZSUSMC). These modulation schemes are used for avoiding the switching states

most contributing to the CMV during a switching period. The effectiveness of the modulation strategies in reducing the CMV of ZSUSMCs is verified through the setup consists of an OP4510 real-time simulator from Opal-RT Technologies Inc. and a TI TMS320F28335 DSP [115].

Noroozi *et al.* have proposed a modified space vector modulation based on the Fourier transform analysis to reduce the leakage current in a three-phase qZSI. The common mode voltage harmonic content in a qZSI contains low and high-frequency harmonics which cause safety and EMI problems can be reduced by this modulation method and suitable filtering respectively, which are validated experimentally [116].

Guo have presented a new modulation strategy for leakage current reduction in the Z-source three-level four-leg inverter. A new carrier-based modulation strategy is proposed by utilizing the effective large, medium, small, and zero vectors, instead of the invalid vectors, to achieve the constant common mode voltage, as well as the leakage current suppression. The proposed solution is carried out on the texas instruments (TI) TMS320F28335 DSP + Xilinx XC3400 FPGA digital control hardware platform. The experimental results verify the effectiveness of the proposed solution [117].

Xu and Ran have developed a novel multi objective control strategy for the three-phase q-ZSI.A SMC-based controller is used to regulate inductor current through shoot-through ratio, and DC-link voltage reference is considered as an additional control input to keep q-ZS network capacitor voltage at a desired constant level. The load current is regulated by a proportional resonant controller whose output is then divided by DC-link voltage reference to obtain a modulation signal. The SMC-based controller for inductor current has the advantages of easy implementation, strong robustness, fast response, and low current ripple. The capacitor voltage is kept constant by the proportional integral-based variable DC-link voltage reference theme with negligible steady-state error and load current is pure sinusoidal with low THD. Simulations are carried out in MATLAB/Simulink and experimental results are controlled through TMS320F28069 floating-point digital signal processor to verify the effectiveness of the proposed control strategy [118].

Qureshi *et al.* proposed a constant frequency double-integral sliding mode controller (DISMC) for the regulation of a four-quadrant continuous gain DC-DC converter based on quasi-Z-source topology. This circuit uses minimum number of passive devices and active switches to provide bidirectional current and bipolar output voltage, making it preferable to use in renewable energy or motor drive applications that require a four-quadrant operation. The proposed controller eliminates steady-state errors and provides robust control in the face of large input voltage or load variations. It enables the converter to provide a fast dynamical response over a wide operating range. Simulations of the proposed controller have been performed in MATLAB/Simulink, where the results of DISMC have also been compared with those of single integral sliding mode control [119].

Xu *et al.* proposed and investigated three new modulation schemes for three phase Z source converters, which are capable of having bi-directional operation as rectifiers, thus have great potential for applications in the field of transportation electrification such as vehicle-to-grid (V2G) chargers. The effectiveness of the proposed method has been fully validated in MATLAB/Simulink simulations and RTLAB Hardware-In-Loop (HIL) experiments based on the real time simulator OPAL-RT OP4510 [120].

Hang *et al.* have developed an improved sinusoidal pulse width modulation (ISPWM) technique carried out to obtain pure sine waves for voltage and current signals in qZSIs in the load side. This switching method can be examined to two and multi-phase approaches simply through the addition of the same controller structure to per phase to obtain higher voltage gains at the output ends of this inverter. A positive rectified voltage at the output point of the QZSI and positive and negative rectified voltages at the output terminals of the QZSI is generated in two-phase approaches to improve the quality of the output voltage of the F-bridge inverter (FBI). These rectified voltages are applied to the FBI block and pure sine waves to obtain the load current and voltages and 1.34% of the Total harmonic distortion (THD) for the output voltage has been reported in the one-phase system while 0.88% of THD has been obtained in the two-phase approach. Reliability of the QZSI was tested through the mean time to failure (MTTF) analysis with the values of the proposed components, shows a very good result for the long-life of the converter. All experimental and simulations steps have been obtained for the same values of the components to support and confirm the accuracy and correctness of the proposed IMSPW [121].

Liu presented a detailed analysis of modulation effect on the reliability and harmonic performance of qZSIs. A comparative evaluation of current stresses, power losses, thermal stresses, number of cycles to failure of the power devices, and the output current harmonics is performed for various modulation strategies such as MBSV, SBMSV, MBMSV, ZSVM6, ZSVM4, SBC, MBC, and MCBC. This comparative analysis enables the researchers to select the appropriate modulation strategy for the qZSI for their applications. Analytical expressions of current stresses and power losses are extracted for selected modulation strategies. Simulations and experiments are carried out to validate the analysis and comparison [122].

6. DISCUSSION ON SOME SPECIAL TYPE OF Z SOURCE CONVERTERS

This section deals with some special type of Z source converters such as trans Z source/ Y source/ Γ-Z-source /T source converters which are used for AC–AC, DC-DC conversions for renewable energy applications.[123]-[135].

He *et al.* had extended the trans-Z-source concept to AC-AC power conversion and fabricated single-phase trans-Z-source AC-AC converter with self commutation strategy in the laboratory and the results are validated [123].

Kojabadi *et al.* have experimented leakage inductance effect on the boosting ability of the transformer-based Z-source (trans-Z-source) inverters through detailed theoretical and mathematical analysis combined with various PSIM based simulations and experimental evaluations [124].

Nguyen and Tran proposed a new single-phase single-stage switched-boost inverter with four switches having the features as continuous input current, buck/boost voltage with single-stage conversion and shoot-through immunity. A 800 W prototype is built with an 110 V/50 Hz output voltage in stand-alone and grid-connected modes. PSIM simulation and experimental results are carried out and it matches with that of the theoretical analysis [125].

Sahoo and Keerthipati discussed about three level voltage source boost inverter to achieve rated three level AC output voltage in a single power conversion stage and even operate in open circuit failure to give rated balanced AC voltage at load using a unipolar pulse width modulation technique. The proposed inverter is verified by simulation (in MATLAB/Simulink) and experiment with the help of a laboratory prototype [126].

Do and Nguyen have proposed a three-level quasi-switched boost T-type inverter suitable for low-power and medium-power applications such as photovoltaic systems, fuel cells, and motor drives with a novel pulse width modulated control method to reduce the inductor current ripple by maintaining shoot-through duty cycle as constant to keep the modulation index as high as possible to have improved voltage gain and shoot through immunity. The steady-state analysis, operating principles, and comparisons with the impedance source-based 3L inverters are presented with PSIM simulation and construction of 1-kW prototype based on the DSP TMS320F28335 microcontroller [127].

Fang *et al.* presented improved Y-source dc-dc boost converter topology having higher voltage gain, continuous input current and small inrush current and flexibility in designing winding magnetics. The simulation and the experiments based a low-power open-loop test prototype is set up in the laboratory using DSP TMS320F2812 to output a set of complementary PWM pulse signals to control the on and off of the switches [128].

Liu *et al.* has developed switched Z-source/quasi-Z-source DC-DC converters (SZSC/SQZSCs) for the PV grid-connected power system. The performances of the proposed converters having two switches and passive elements like inductors and capacitors, including their operational principles in continuous and discontinuous current modes, voltage and current parameters of components, and impacts of parasitic parameters, are analyzed. PSIM simulation and experimental results are given to verify the aforementioned characteristics and theoretical analysis [129].

Kafle *et al.* presented a quasi-Z-source based isolated bidirectional DC-DC converter (qZIBDC) for renewable energy applications. This converter utilizes a dual active bridge circuit with a quasi-Z-source network on both sides, so the converter works as buck/boost converter from either side. It has a wider input/output voltage operating range, soft-switching capabilities without additional devices, and higher boost capability than a traditional dual active bridge circuit. Apart from that, shoot-through states are incorporated in its operating cycle to boost the input voltage resulting in high reliability of the proposed converter. Due to the symmetrical structure of the circuit, there is no defined high voltage or low voltage side as in traditional isolated bidirectional DC-DC converter. The operating principle and control strategy of the proposed converter are presented. Matlab based simulation and experimental results for 300 W prototype are provided for various values of duty cycle to verify the effectiveness of the proposed converter topology and its control strategy [130].

Kumar *et al.* proposed a coupled inductor network based on the autotransformer concept known as quasi mutually coupled active impedance source converter, which has a continuous input current for reducing the current stress on the source. The operation, steady-state analysis and its comparison with the existing topology are discussed and it is validated to prove its feasibility [131].

Nguyen *et al.* proposed a single-stage active impedance source three-phase T-type inverter with a reduced component count. Besides the inherent features of the three-level impedance source inverters like shoot-through (ST) immunity, single-stage power conversion, and continuous input current, the proposed inverter has additional advantages such as increased voltage gain, reduced passive element count, low voltage stress on devices and self-balance capacitor voltage capability. The steady-state analysis, operating principles, and parameter selection guidelines are presented in detail. PWM techniques for the proposed

inverter including the sinusoidal PWM method and modified space-vector modulation scheme for common-mode voltage reduction are also presented. A comprehensive comparison between the proposed inverter and other three-level impedance-source inverters are shown. The proposed inverter has been validated using the PSIM simulation software and a 1 kVA laboratory prototype, in which DSP TMS320F28335 controller is used to generate the PWM control signals for the switches, has been constructed to verify the performance of the proposed inverter [132].

Reddivari and Jena have presented negative embedded differential mode gamma source inverter (NEDMΓZSI), which can achieve higher voltage gains with reduced switching voltage spikes and low capacitor voltage stresses. It draws continuous input current from the dc mains, having a common ground, and uses the minimum number of component in a circuit. The performance of a NEDMΓZSI is validated with simulation and experimental verification using a single-phase inverter configuration [133].

Torkaman *et al.* studied a hybrid AC/DC microgrid with bidirectional Γ-Z-source inverter as an interlinking converter (IC). The Γ-Z-source inverter is capable of providing high-voltage gain and it does not have the drawbacks of the conventional inverters. In this hybrid microgrid, DC-type energy sources and loads are connected in DC sub-grid and AC-type energy sources and loads are connected in AC sub-grid to reduce the extra power conversion stages in both AC and DC sub-grids which decreases the system volume and cost and increases the system reliability and efficiency. The individual DC–DC power converter, a MPEI, is used for interconnecting DC distributed generators consisting of photovoltaic system and battery unit. They also presented the control of three operation modes including grid-connected mode, islanded mode and islanded mode with power flow management and the IC and distributed generators and for power sharing management, droop strategy is used. The performance of the proposed IC in all three operation modes is evaluated by time domain simulations in MATLAB/Simulink [134].

Zhang *et al.* proposed a novel electric spring topology with a specifically designed impedance network, which intrinsically has a wide voltage range and immune to the bridge shoot-through. Detailed theoretical derivation, simulation and experimentation are conducted to verify its advantageous features by demonstrating a wide voltage operation range, undistorted waveforms and safe operations [135].

7. Z SOURCE CONVERTER TOPOLOGIES FOR VARIOUS ELECTRICAL APPLICATIONS

This section deals with various applications of Z source converter topologies such as photovoltaic systems, fuel cell vehicles, hybrid energy sources, FACTS, custom power applications, on board charger for electric vehicle applications and electric drive /water pumping applications [136]-[148].

Zhang *et al.* had worked out a quasi Z source boost DC-DC converter which uses a switched-capacitor for fuel cell vehicles producing a high voltage gain with a wide input-voltage range. A scaled-down 400V/400W prototype is developed to validate the results with the help of PI controller in the voltage loop using DSP platform operated under dynamic conditions [136].

Zhang *et al.* have developed a common ground switched-quasi-Z-source bidirectional DC–DC converter for electric vehicles with hybrid energy sources having the advantages of a wide voltage-gain range, lower voltage stress across the power switches, and an absolute common ground. A 300 W prototype is fabricated which operates at wide input voltage range and the experimental results are validated in both step up/step down mode. This topology can be applied as the power interface between the low-voltage battery pack/super capacitor bank and the high-voltage dc bus in the hybrid energy sources system for electric vehicles [137].

Law had worked out type 2 based closed loop voltage controller with novel dc link voltage reference algorithm to fulfill the dc link voltage tracking control of a single phase qZSI regardless of any loading conditions, without the need of inner inductor current loop for STATCOM operation. The integrated controller and qZSI topology is then employed in static synchronous compensator application to perform reactive power compensation at the point of common coupling. The effectiveness of the proposed approach is verified through simulation and experimental studies [138].

Na *et al.* had implemented an active power filter (APF) for single-phase quasi-Z-source rectifier. It eliminates the second harmonic power with small capacitor and inductor, making this topology suitable to integrated electric vehicle (EV) on-board charger, which can save much space and weight. Simulation and experimental results of 750 W are used to verify its effectiveness [139].

Omran and Mosallanejad have proposed bidirectional ZSI to manage the novel hybrid energy storage system composed of battery pack and superconducting magnetic energy storage for electric vehicle to have increased power and energy density. Fuzzy control method and filters are used to distribute power between the SMES and battery which are illustrated through sample simulations [140].

Meraj *et al.* have developed modified pulse width modulation technique to control the qZSI, to reduce the common mode current. This approach offers an efficient solution for grid integration of solar

photovoltaic systems having the features such as: a) use of phase-leg shoot-through for boosting the DC voltage to the required level which eliminates the additional DC-DC converter, b) elimination of PWM dead-time and providing freewheeling through additionally connected switches, c) minimization of common mode current by modifying the PWM and adding additional switches at the output side of inverter, d) avoids the conduction of body diode of H-bridge which has poor reverse recovery characteristics. Experimental results for a single-phase 500W prototype are presented to validate the proposed PWM scheme for the qZSI topology. The control code is written in system generator and built using FPGA VIRTEX-5 XC5VLX50T [141].

Sajadian *et al.* have proposed a maximum power point tracking (MPPT) method for the grid tied Z source inverter that interfaces photovoltaic sources to the grid. This method uses model predictive control (MPC) in conjunction with extremum seeking (ES) optimization algorithm to track the true maximum power point and can operate without priori knowledge of the PV panel parameters or ambient condition. At the grid side, the system injects to the grid maximum harvested energy from the PV panel obtained using the proposed MPPT algorithm. In addition, the ratio of active/reactive power injected to grid is also controlled. The proposed method has the features like fast dynamic response to change in ambient PV panel condition, true and guaranteed convergence to MPP, negligible oscillation around MPP, and simple control structure without requirement of many cascaded control loops [142].

Shuai *et al.* discussed about qZSI powered PMSM drive system. A feedback and feed forward compound control strategy is proposed and the dynamic performance of this drive system is analyzed. Simulation and experimental results indicate that the compound control strategy effectively improves the static and dynamic characteristics of the DC-link voltage and reduces the influence of power variation on the DC-link voltage [143].

Liu *et al.* have proposed CMV reduction method for the APF integrated single-phase qZSI based PV power system. The APF integrated qZSI completely compensates the dc-side double-line-frequency (2ω) ripple through the APF capacitor, while maintaining low qZS inductance and capacitance. This method reduces the CMV amplitude to half of that using the traditional sinusoidal pulse width modulation (SPWM). The switching and conduction power losses are analyzed. MATLAB/Simulation and experimental results are demonstrated in TMS320F28335 digital signal processor to reduce the CMV without comprising performance and efficiency of the APF integrated single-phase qZSI [144].

Na *et al.* have proposed a soft switched modulation technique for the single-phase quasi-Z-source integrated electric vehicle charger (qZSC) system which can achieve multiple zero-voltage-switching (ZVS) and zero-current-switching (ZCS) transitions without any auxiliary circuit. The inductor currents of the quasi-Z-source network operate in boundary conduction mode (BCM) or discontinuous conduction mode (DCM) to achieve all free-wheeling diodes turned off naturally without any additional voltage stress and current stress on all switches in comparison with hard-switching. The details of operation principles of this soft-switching qZSC are analyzed through a PLECS simulation model and a 1.3-kW prototype is established [145].

Dong *et al.* discusses about finite set model predictive control method used for quasi-Z source inverter-permanent magnet synchronous motor drive system having the characteristics such as quicker response speed and stronger anti – disturbance ability. Here the control variables of quasi Z source network and motor are controlled uniformly, to avoid the conflicts between the shoot through duty cycle and the inverter modulation coefficient during the dynamic adjustment process in the traditional two stage control method. Steady state, dynamic and input voltage dip experiments are performed on the qZSI permanent magnet synchronous motor drive system to verify it's the effectiveness [146].

Wu *et al.* proposed a DC link voltage control strategy for high speed permanent magnet motor drive systems powered by ZSI. In this strategy, the DC-link voltage, varies with the inverter output voltage and remains optimal at all times, whether in steady state or transient state. A new sliding mode control system based on indirect control of the capacitor voltage is used to control the DC-link voltage to suppress the system fluctuation caused by the change of the given value or the motor load. Simulations and experiments verified the effectiveness of the proposed strategy [147].

Rahman *et al.* has presented design and implementation of solar powered V/f controlled single phase capacitor start induction motor. Here, multi level quasi impedance source inverter (MLqZSI) is used to ensure reliable and continuous power flow to single phase induction motor from PV array supported with battery storage system to overcome solar PV fluctuations. MATLAB/ Simulink model of the proposed system for 4kW PV array rating is developed and satisfactory operation of single phase motor drive is achieved through experiments [148].

8. CONCLUSION

In this paper, a detailed literature is carried out on the developments made in the field of Z-source converters and their implementation discussing the new Z source/quasi Z source structures predominantly used for various renewable energy applications. Emerging control strategies developed for the functioning of these converters in various operating platforms are also discussed.

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